REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT DATE	3. DATES COVERED *(From - To)*
26-02-2004	Final report	11/1/02 - 9/30/03

4. TITLE AND SUBTITLE
Nonclassical Effects in Quantum Optics

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-03-1-0180

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Unrestricted

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20040303 267

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Several experimental and theoretical investigations in quantum optics were performed under this grant, with potential applications for improved gyroscope performance, more accurate clock synchronization, and quantum communications and information processing. A controlled-NOT quantum logic gate for single photons was experimentally demonstrated for the first time. Several methods for generating nonclassical states of light as needed for various applications were investigated theoretically. Methods for improved single-photon detection efficiency were demonstrated experimentally and investigated theoretically.

15. SUBJECT TERMS
Quantum Logic Photon Computer

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPONE NUMBER *(Include area code)*
U	U	U	UU	7	J. Franson / 443-778-6226

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

Nonclassical Effects in Quantum Optics

ONR Grant # N00014-03-1-0180

Final Report

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26 February, 2004

Introduction

The overall objective of this program was to investigate new phenomena in quantum optics that are of fundamental scientific importance as well as having potential applications for Navy programs, such as improved gyroscope performance or more accurate clock synchronization. Results from this year's research are also expected to have applications in quantum information processing and secure communications.

One of the objectives for this year was to develop methods for generating the nonclassical states of light that are required for clock synchronization and quantum information processing. A linear optics approach to quantum logic operations has the practical advantage that it requires only simple optical elements, such as beam splitters and phase shifters, that are available commercially. But in order to use these techniques, it is necessary to generate entangled states of additional (ancilla) photons to be used as a resource. The development of methods for the generation of nonclassical states of light as well as improved quantum logic devices was therefore one of the main objectives for this project.

The ability to detect single photons with high probability has a number of potential applications, including low-intensity sensor systems, clock synchronization using quantum-mechanical techniques, and quantum information processing. Another goal for this project was to investigate ways to improve the performance of existing single-photon detector technology using interferometric and other techniques.

Technical Approach

Our approach for the generation of nonclassical states of light includes the use of linear optics techniques for the construction of quantum logic gates. The quantum logic gates can then be used to generate an arbitrary quantum state of light starting from a source of independent single photons. Various methods for the generation of nonclassical states of light are being investigated, including the use of quantum error correction techniques to reduce the probability of obtaining incorrect output states. Experimental demonstrations of the basic quantum logic gates, such as a controlled-NOT gate, are an important part of this approach. The use of solid-state devices for the generation of nonclassical states of light is also being investigated.

Improved single-photon detection efficiency is being investigated in several different ways. One approach is to increase the efficiency of commercially-available detectors by taking the light that is reflected from one detector and focusing it back onto a second detector. Another approach is to carefully balance an interferometer containing n incident photons in such a way that no photons exit from one of the output ports. The presence of a single additional photon can then unbalance the interferometer and produce a large output signal that can easily be detected.

Accomplishments

One of our main accomplishments was the first experimental demonstration of a controlled-NOT logic gate using single photons as the qubits. These devices are the basic building-block of a quantum computer and they play an essential role in other tasks, such as the generation of nonclassical states of light for improved gyroscope performance and quantum repeaters for secure communications systems. A controlled-NOT logic gate was demonstrated in optical fibers using the apparatus shown in Figure 1. Typical experimental results are shown in Figure 2.

Another accomplishment was the development of several different methods for generating the entangled ancilla states required as resources for a linear optics approach to quantum logic. We showed that the required nonclassical states could be generated using elementary logic elements, such as the controlled-NOT gate that we experimentally demonstrated. A solid-state device that is capable of generating these states directly was also investigated theoretically and is shown in Figure 3.

In the area of improved single-photon detectors, we showed experimentally that the detection efficiency of existing detectors could be improved by focusing the light reflected from one detector onto a second detector. This resulted in a modest improvement in the detector efficiency from 70% to 80%. Theoretical analysis was also performed to show that interferometric techniques can be used to detect single photons with arbitrarily high efficiency using low-efficiency detectors.

Another accomplishment was the development of single-photon detectors that can determine the number of photons present in an optical pulse. Conventional detectors cannot distsinguish between one or more photons, and simply produce an output pulse whenever one or more photons are incident. We developed a time-multiplexing technique illustrated in Figure 4 that allowed ordinary silicon avalanche photo-detectors to serve as number-resolving detectors. The basic idea is to split the incident pulse into a large number of smaller pulses that are separated in time. This allows two ordinary detectors to measure the total number of photons, as illustrated by the experimental data in Figure 5.

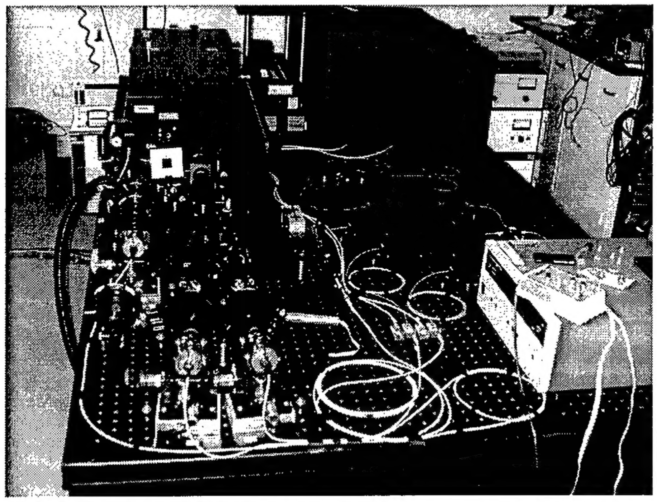

Figure 1. Experimental apparatus to perform the first demonstration of a controlled-NOT quantum logic gate for single photons.

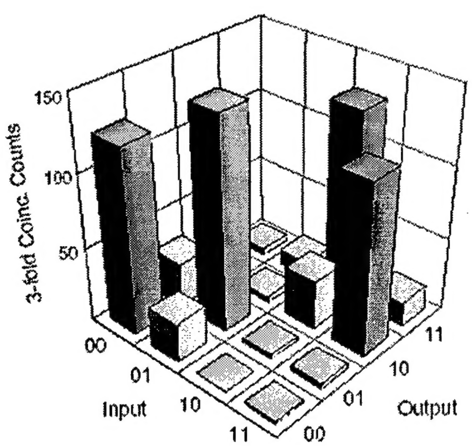

Figure 2. Typical experimental results obtained from a controlled-NOT logic gate.

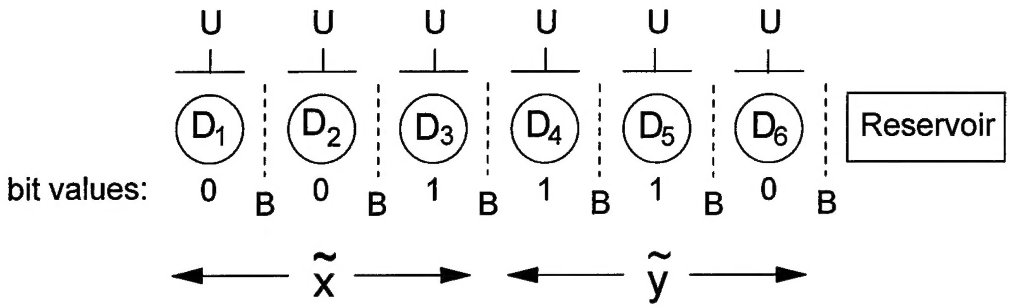

Figure 3. Solid-state device capable of directly generating entangled states of photons.

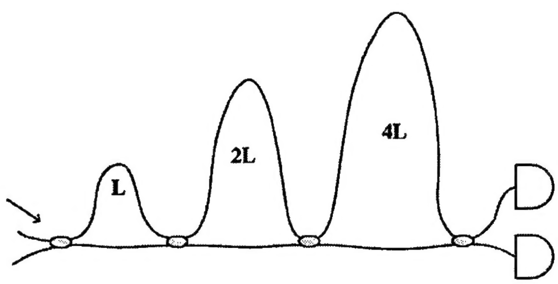

Figure 4. Time-multiplexing technique that allowed ordinary single-photon detectors to resolve the number of photons in an optical pulse.

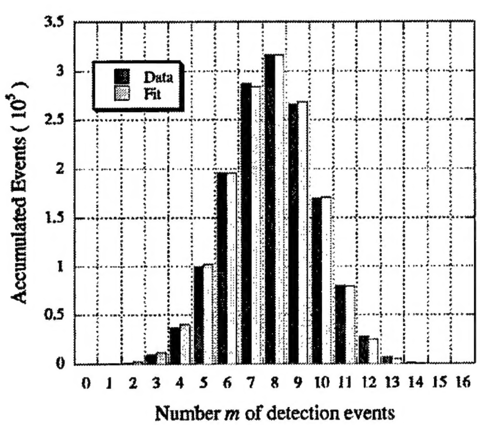

Figure 5. Experimental results obtained from the time-multiplexed photon detector system.

Publications:

1. "Experimental Progress in Linear Optics Quantum Computing", J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, Quantum Information and Control **3**, 553-562 (2003).

2. "Generation of Entangled Ancilla States for use in Linear Optics Quantum Computing", J.D. Franson, M.M. Donegan, and B.C. Jacobs, submitted to Physical Review A.

3. "Violation of Bell's Inequality with Photons from Independent Sources", T.B. Pittman and J.D. Franson, Physical Review Letters **90**, 240401-1 to 240401-4 (2003).

4. "Experimental Controlled-NOT Logic Gate for Single Photons in the Coincidence Basis", T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, Physical Review A **68**, 032316 (2003).

5. "Heralded Two-Photon Entanglement from Probabilistic Quantum Logic Operations on Multiple Parametric Down-Conversion Sources", T.B. Pittman, M.M. Donegan, M.J. Fitch, B.C. Jacobs, J.D. Franson, P. Kok, H. Lee, and J.P. Dowling, submitted to the IEEE Journal of Selected Topics in Quantum Electronics.

6. "Photon number resolution using time-multiplexed single-photon detectors", M.J. Fitch, B.C. Jacobs, T.B. Pittman, and J.D. Franson, Physical Review A **68**, 043814 (2003).

Presentations:

1. "Progress in Linear Optics Quantum Computing", J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, 33rd Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT, 5-9 January, 2003. (Invited).

2. "Demonstration of Quantum Logic Operations Using Linear Optical Elements", B.C. Jacobs, M.M. Donegan, M.J. Fitch, T.B. Pittman, and J.D. Franson, U.S.-Australia Workshop on Solid State and Optical Approaches to Quantum Information Science, Sydney, Australia, 7 January 2003. (Invited)

3. "Need for High Efficiency Photon-Number Resolving Detectors in Linear Optics Quantum Computing", T.B. Pittman, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and J.D. Franson, NIST-ARDA Workshop on single-photon detectors, Gaithersburg, MD, March 31, 2003.

4. “Experimental Controlled-NOT Logic Gate for Single Photons”, T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, Gordon Research Conference on Quantum Information Science, Ventura, CA, March 23-28, 2003.

5. “Quantum Computation with Linear Optics”, M.J. Fitch, M.M. Donegan, T.B. Pittman, B.C. Jacobs, and J.D. Franson, 17^{th} International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, Orlando, FL, 21 April 2003. (Invited).

6. “High-Fidelity Quantum Logic Operations and Entangled Ancilla States”, J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

7. “Improved Single-Photon Detector Performance, M.J. Fitch, M.M. Donegan, B.C. Jacobs, T.B. Pittman, and J.D. Franson, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

8. “Quantum Logic Operations in Optical Fibers”, B.C. Jacobs, T.P. Pittman, M.J. Fitch, and J.D. Franson, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

9. “Violation of Bell’s Inequality with Photons from Independent Sources”, T. B. Pittman and J.D. Franson, 87^{th} OSA Annual Meeting, Tucson, AZ, October 5-9, 2003.

10. “Linear Optical Quantum Computing”, J.D. Franson, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, 87^{th} OSA Annual Meeting, Tucson, AZ, October 5-9, 2003. (Invited)